A Seismic Refraction Study of the Koolau Volcanic Plug[1]

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ABSTRACT: The seismic data from the GASHOUSE line support the gravity and magnetic data as indicating a plutonic body occurring beneath the center of the Koolau caldera in the vicinity of Kailua, Oahu. This plug has a velocity greater than 7 km/sec and adjoins material with a velocity of about 4.6 km/sec at the top and to the southeast. The width of the plug is estimated to be about 6 km down to 3–4 km. Reflections from a horizon greater than 3 km deep may indicate an underlying magma chamber. The top of the plug is about 1600 m deep.

Drilling of this plug would have considerable scientific value both geologically and geophysically. An appropriate drilling site would be at the southwest corner of Kaelepulu Pond, which lies close to the center of the plug as now defined geophysically. Seismic reflection work directly above the dome is also recommended to test the present estimate of the depth based on refraction results.

GRAVITY MEASUREMENTS on the windward side of Oahu define a local anomalous high of about +110 mgal. This was first reported by Woollard (1951), and subsequently has been surveyed in more detail by the Institute of Geophysics. Woollard interpreted this anomaly as being caused by high density (3.2–3.3 g/cc) pipe material extending to within 1–2 km of the surface. A more recent analysis (Strange, Woollard, and Rose, p. 381 in this issue) arrives at much the same conclusion. Although the initial intention of the seismic work reported here was to "fan shoot" the plug, as well as to determine its velocity and depth, the over-all difficulty of the experiment and higher-than-anticipated costs dictated that part of the operation be curtailed. It was decided that the depth and velocity of the plug—as possible mantle material—was of greater interest than the extent. Therefore, all work has consisted of in-line refraction shooting in order to obtain estimates of the seismic velocity in the plug and the depth to the top of the plug.

PREDICTION TECHNIQUE EMPLOYED

Previous seismic work on plugs has been concerned mostly with exploration for oil around salt domes. The objective in such work is to define the flanks of the dome so that exploratory drilling can be conducted. There is very little interest in the velocity or shape of the top surface of the dome, and a satisfactory estimate of the depth of the dome can usually be obtained from reflections or from potential methods since the density of salt is quite uniform from dome to dome. Investigations of buried volcanic plugs have been few and mostly unsuccessful. Thus, the present investigation is relatively unique in that it appears to have been a success. This can be attributed in large part to planning of the field work.

A theoretical model was first constructed based on the gravity estimates of the depth and size of the plug and seismic velocities determined from short exploratory refraction spreads. The model used is shown in Figure 1. The velocities at depth were taken from preliminary estimates on the ABLE line running to the northwest along the northern shore of Oahu (Furumoto, Thompson, and Woollard, p. 306 in this issue). The features in the resulting theoretical travel-time curves are the usual crossovers, but with the 6.2 km/sec leg being shifted downward at greater distance, similar to that which occurs on the down-thrown side of a normal fault (see, for example, Nettleton, 1940:272). In addition, there are later arrivals in the region of the start of the downward diffraction distance

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and usually at shorter distances, which correspond to head waves that are refracted upward from the top of the plug. It is these head waves which permit an estimate of the velocity in the plug.

Note that this program was initiated with the expectation that the data desired would occur as second arrivals. It should also be noted, however, that if the plug extends upward to a sufficiently shallow depth, then the refraction segment will move downward across the 6.2 km/sec leg and actually be composed of the first arrivals. In this case, the end of the refraction segment would still taper off into the diffraction zone. Another point of interest in connection with this model is that if the plug does not completely penetrate the 6.2 km/sec layer, double arrivals at distances greater than the diffraction distance are to be expected. If the plug does completely penetrate this layer, then the 6.2 km/sec leg would not be extended.

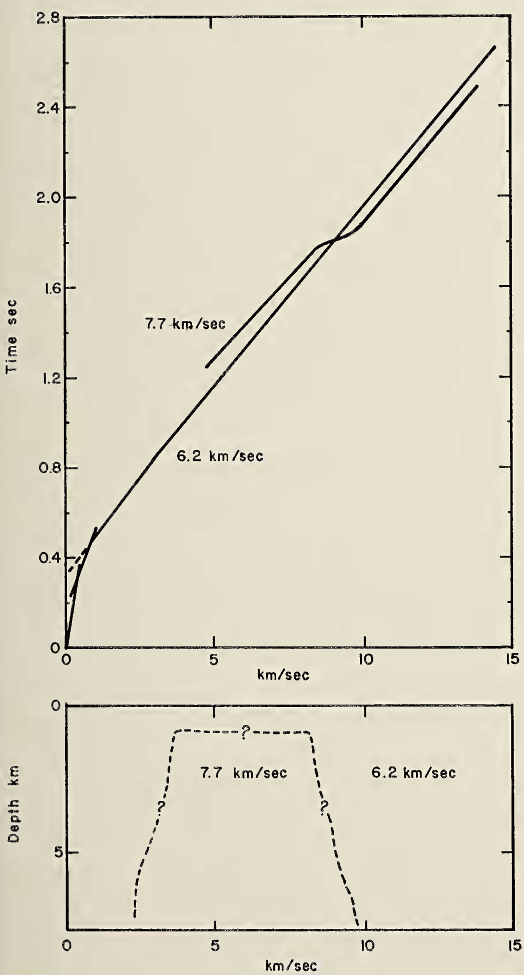

FIG. 1. Structural model used for planning seismic field effort.

FIELD PROGRAM

A location map of the area of interest is shown in Figure 2. The other seismic lines established by the Hawaii Institute of Geophysics—ABLE, BRAVO, and DELTA—are also shown. The area of interest is denoted by the block oriented NW–SE. This is shown in detail in Figure 3.

The gravity high defining the Koolau caldera lies on the present coastline and adjoins Kaneohe Bay. Because the caldera is now a residential area, Kaneohe Bay provided the only feasible area for shooting charges large enough to obtain data over the ranges required. The initial field effort was confined to the caldera, but it soon became apparent that operations restricted to this area would not yield satisfactory data because of the slope-effect of the buried caldera walls, which on some spreads resulted in infinite apparent velocity values. The shot line finally established based on the model analysis extends across the center of the gravity high with relatively slight deviations of stations from a straight line, except in the vicinity of Kawainui Swamp where transportation was restricted. An effort to use U. S. Marine personnel carriers to work straight across the swamp ended in failure when the vehicles became hopelessly bogged down.

All the shots that were conducted for recording along this line are listed in Table 1. Each shot was recorded with 250-ft spreads at two positions. Each shot consisted of 50 lb of Nitramon detonated on bottom at a depth of 50 ft at the location of Buoy 27 in Kaneohe Bay. It was hoped that shooting on bottom would give maximum seismic energy coupling and minimize the bubble pulses (Worzel and Ewing, 1948:18). Larger charges could not be shot due to cultural restrictions.

The usual field difficulties due to imperfections of men and machines were encountered. Sample records are shown in Figure 4. The paper speeds used were 2 inches/sec or 8

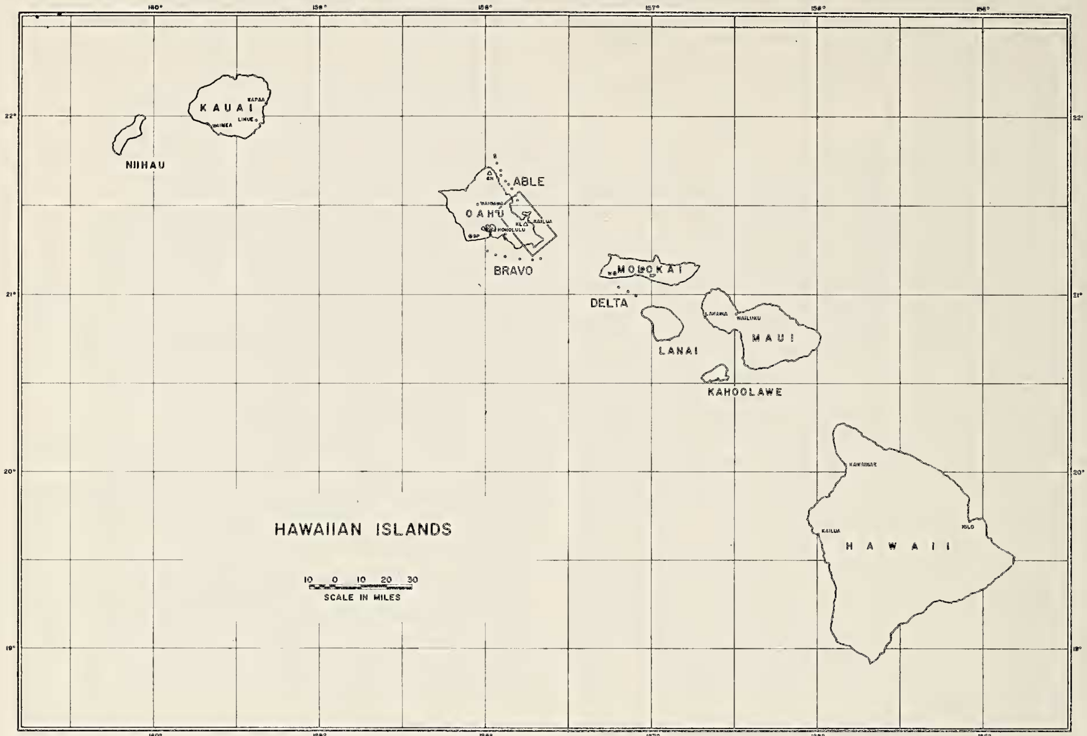

FIG. 2. Location map of the seismic field program.

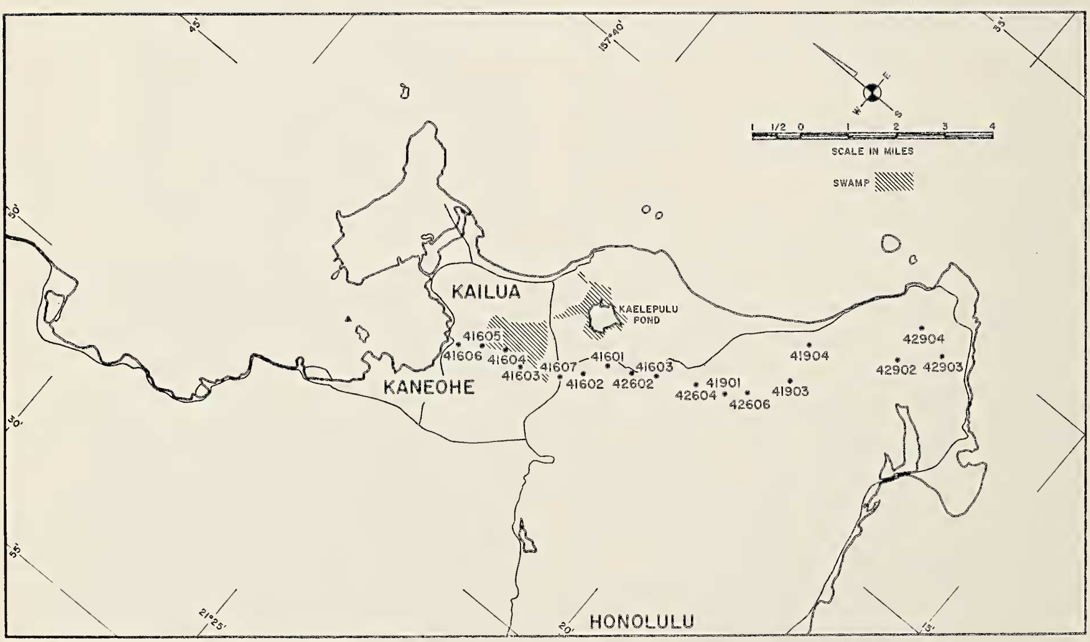

FIG. 3. Location map of the field stations in the vicinity of Koolau caldera.

inches/sec. Some of these records will be referred to later, under the section on interpretation, as they are critical to the analysis.

Important travel-time picks taken from the seismograms are listed in Table 2. Although the values are given to a millisecond, the data are not necessarily reliable to better than 10 milliseconds. Because of the short spread-length (250 ft) necessary, apparent velocities are not given as they are not regarded as having any real significance.

INTERPRETATION OF DATA

The writers' interpretation of the data is presented in Figure 5 as a standard travel-time graph. The sample record locations are noted, and the reader should refer to them as needed while reading the remainder of this section on interpretation. The present interpretation is not the first derived, nor the one presented by Furumoto at the Eastern Section of the Seismological Society of America (Furumoto, 1964). The change in interpretation resulted from subsequent additional shooting.

The most prominent feature on the records and on the travel-time plot of the data is the strong, frequent occurrence of a second arrival about 0.450 sec after the initial motion. This has been interpreted as being a bubble pulse. The theoretical time-delay value that should be obtained for a shot in a 50-ft depth of water, neglecting the bottom effects, can be obtained from the equation

$$T = 4.19 \frac{W^{1/3}}{(H + 33)^{5/6}}$$

where H is the depth in feet of the shot point, and W is the weight of explosive in pounds. From this calculation, we obtain 0.368 sec, which is considered to be in satisfactory agreement with the observed interval of 0.45 sec since bottom effects have been ignored. From the sample record corresponding to a distance of 3.79 km (Fig. 4), the similarity of the bubble pulse to the initial motion in both ampli-

TABLE 1

TIME AND LOCATION OF SHOTS FOR THE SEISMIC REFRACTION STUDY*

			WHITE TRUCK		GREEN TRUCK	
SHOT NO.**	DATE	TIME	Distance (km)	Elevation (ft, ± 5 ft)	Distance (km)	Elevation (ft, ± 5 ft)
4T601	10/1/64	0929	7.99	190	not recorded	
4T602	"	0932	not recorded		8.78	280
4T603	"	1021	5.94	140	9.62	260
4T604	"	1103	5.35	0	10.43	40
4T605	"	1145	4.55	40	11.70	140
4T606	"	1230	3.79	20	not recorded	
4T607	"	1330	7.27	100	13.51	95
4T901	11/15/64	1330	12.70	100	not recorded	
4T902	"	1400	not recorded		18.10	40
4T903	"	1450	14.80	200	19.50	90
4T904	"	1540	15.20	400	18.90	70

* All charges were 50 lb at 50 ft deep in 50-ft depth of water (on bottom).
** T = 1 for white truck, 2 for green truck.

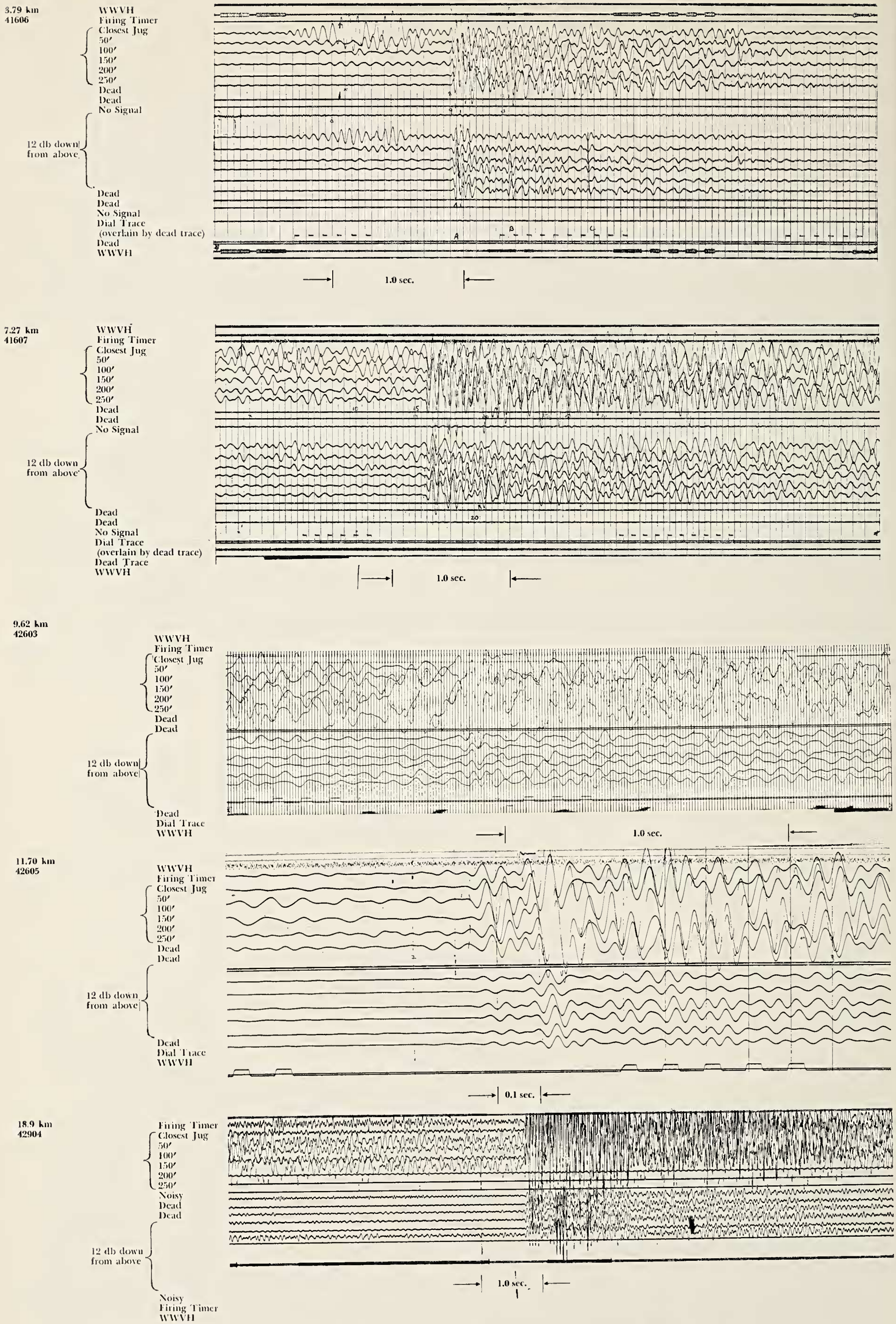

FIG. 4. Sample records taken in the refraction field effort.

tude and character can be seen. This occurrence of strong bubble pulse was especially annoying in this study in which secondary arrivals were expected to play a prominent part in the results.

From the travel-time plot, it is seen that the first arrivals align well out to 7.27 km. Beyond this point this line can be extended on the basis of secondary arrivals at distances of 8.8 km, 12.7 km, 18.1 km, etc.

The portion of the plot showing a downward shift in the arrival of first motion, initially attributed entirely to diffraction effects, is composed of notably strong arrivals and the bubble pulses duplicate the first motion in this sector. The segment of first motion from 11.7 km outward is definitely early and is parallel to the 4.74 km/sec segment obtained at distances less than 7.27 km. Considering the complexity of the geology in a volcanic terrain, this extreme parallelism was unexpected. (Note, however, that the arrivals at 15.2 km are about 0.085 sec late for both the initial signal and bubble pulse, and that the arrival at the 19.5 km station is 0.123 sec late. Note also that the first arrival at 19.5 km, denoted with a question mark, was definitely a repick and was similar in character to noise in the leading part of the seismogram.)

The computer program for obtaining the best fitting line by least squares has been run on the first arrivals, the bubble pulses, and the early first arrivals. The values obtained are given in Table 3.

Assuming that the top of the plug is approximately parallel to the surface of the ground, the dependency of the first occurrence of refrac-

TABLE 2

ARRIVAL TIMES FROM THE REFRACTION SEISMOGRAMS

DISTANCE (km)	RECORD NO.	1ST ARRIVAL (sec)	2ND ARRIVAL (sec)	3RD ARRIVAL (sec)	4TH ARRIVAL (sec)
3.79	41606	0.840	1.260	1.845	....
4.55	41605	0.960	1.398	1.870	....
5.35	41604	1.155	1.290	1.610	1.940
5.97	41603	1.295	1.505	1.770	2.090
7.27	41607	1.560	1.755	2.060	2.770
7.99	41601	1.640	1.800	2.140	2.380
8.78	42602	1.790	1.910	2.240	2.500
9.62	42603	1.848	1.948	2.288	....
10.43	42604	1.988	2.408	2.758	2.848
11.70	42605	2.115	2.270	2.470	2.970
12.70	41901	2.310	2.730	3.010	3.720
13.50	42607	2.495	2.778	2.875	3.375
14.80	41903	2.790	2.890	3.140	3.270
15.20	41904	2.950	3.140	3.350	3.540
18.10	42902	3.520	3.642	4.050	4.350
18.90	42904	3.680	4.090	4.180	4.580
19.50	42903	3.920	4.290	4.570	4.940

tions upon the depth to the plug and the seismic velocities in the plug and the overlying material can be determined (Fig. 6).

In this analysis we note that for the critical angle (i_c)

$$\sin i_c = \frac{V_o}{V_p}$$

and $$\tan i_c = \frac{h}{H}$$

where H is the thickness of the layer and h the half distance from the point of origin to emergence.

Or if h is observed

$$h = H \tan\left[\sin^{-1}\left(\frac{V_o}{V_p}\right)\right]$$

then

$$H = h/\tan\left[\sin^{-1}\left(\frac{V_o}{V_p}\right)\right]$$

If the plug is of only limited lateral extent, then the diffractions off the trailing edge of the plug will start with the end of the segment of refracted arrivals and cross over the first arrivals to lead into the early portion of the early arrival segment. If, however, the plug is of sufficient lateral extent, then the refraction segment representing the energy traveling through the plug will overtake the first arrivals and may even be composed of the first arrivals. The first case is illustrated in Figure 1, used to predict the expected results; the latter is seen in Figure 5, the interpretation made here. The strong energy in the first motion in the "diffraction" range supports this interpretation.

Based on the slope of the first arrivals at the downward flexure of the travel-time curve, a lower bound of 6.98 km/sec (say 7 km/sec) is obtained for the velocity in the plug. Inspection of the data in Figure 5 on which this is based indicates the relatively poor quality of the estimate.

An estimate of the depth of the dome at the point where the critically refracted ray enters can be obtained by the construction of the aplanatic line in the vertical plane containing both the shotpoint and the detector at the crossover station, 7.27 km. This has been done and the maximum depth is indicated as being 1630 m. This point corresponds to the point of the aplanatic curve which would be intersected by a ray leaving the origin at 42°, hence it is taken to be the depth. The reliability of this depth, then, depends on the validity of the assumption that the top of the plug is hori-

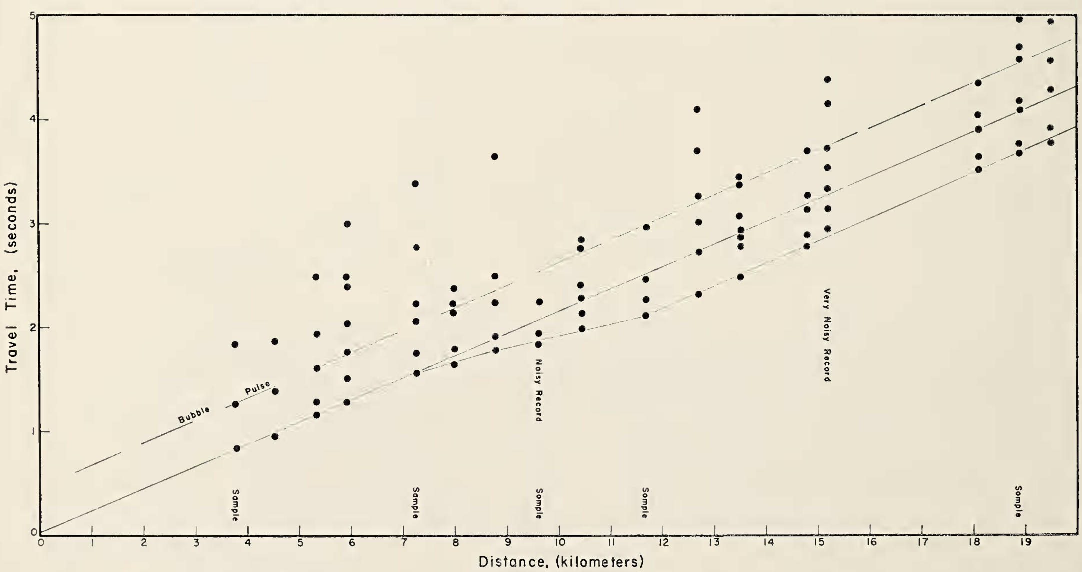

FIG. 5. Interpretation of the travel-time data.

TABLE 3

VALUES OBTAINED FROM COMPUTER PROGRAM RUN ON FIRST ARRIVALS, BUBBLE PULSES, AND EARLY FIRST ARRIVALS

COMPUTER CODE PARAMETER	UNITS	FIRST ARRIVALS	BUBBLE PULSES	EARLY FIRST ARRIVALS
K		1	3	4
N		5	9	6
X BAR	km	5.38	9.49	14.95
T BAR	sec	1.16	2.49	2.83
T RECIP	km	42.25	43.55	42.37
T NULL	sec	0.025	0.453	–0.363
SLOPE	sec/km	0.211	0.216	0.214
APP VEL	km/sec	4.74	4.64	4.68
VAR SLP	$(km/sec)^2$	0.	0.	0.
DEV SLP	km/sec	0.	0.	0.
XDELTA	km	0.	582.25	–448.66

zontal at the point where the critically refracted ray enters. To be conservative in the following developments, we will use the value of 2 km. Actual drilling, however, should intersect the high velocity rock at less than 1630 m.

An estimate of the structure to which the observed travel times correspond is given in Figure 7. This should be compared with the

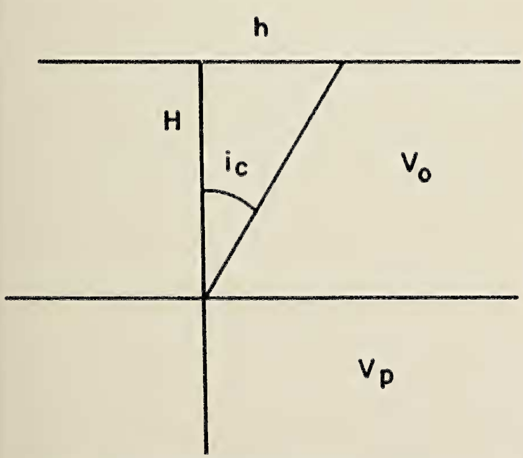

FIG. 6. Relation of refraction arrival section to position of the plug.

preliminary interpretation of line ABLE (Furumoto, Thompson, and Woollard, p. 306 in this issue), northwest from Kailua School, as the velocities obtained in that study have been used to guide this work. Note that the high velocity layer of about 6 km/sec was not observed to the southeast of the pipe in this present study. Because of this, one might be inclined to interpret the data as normal faulting, with the downthrown block on the southeast side. This is impossible because of the high energy arrivals observed in the 3- to 6-km range and arriving after the bubble pulse. These are interpreted as reflections off a possible former magma chamber at a depth of 3–4 km.

An alternative interpretation might attempt to fit the strong reflections arriving at short range with the bubble pulses in the intermediate range and make claim for a high-speed layer. Fortunately, the present survey was continued out to a distance from the shot point sufficient to preclude that possibility. Such a high-speed layer is not possible.

Since secondary arrivals still occur after the diffraction range, corresponding to direct arrivals through the 4.74 km/sec zone, the plug

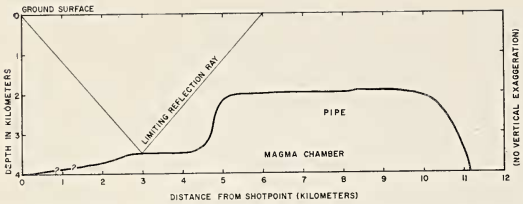

FIG. 7. Structure deduced from the observed refraction data.

does not penetrate the 4.74 zone. As can be seen from the sample record at 7.25 km, the first arrival is especially strong and probably corresponds to the intersection of the direct and the refracted waves.

Using the analysis corresponding to Figure 6 and assuming a depth of 2 km, we obtain an offset for the refracted data of about 1½ km. An estimate of the width of the plug may be obtained from the lead of the early arrival segment occurring after 11.7 km. This segment leads the extension of the previous first arrival curve by 0.410 sec. The meaning of this time lead can be seen from Figure 8.

Two rays are considered traveling from the source, S, to the observer, O, with one passing just above the plug and the other passing through the top of the plug. If we write the time of transit for the upper path as T_u and the time in the lower path as T_l, then

$$T_u = \frac{\overline{SO}}{V_o}$$

$$T_l = \frac{\overline{SO} - L}{V_o} + \frac{L}{V_p}$$

where $\overline{SO}$ is the over-all path distance, L the width of the plug, V_p is the velocity in the plug, and V_o is the velocity in the matrix rock. The difference in arrival time will, therefore, be

$$T_u - T_l = L \left[\frac{1}{V_o} - \frac{1}{V_p}\right]$$

$$T_u - T_l = L \left[\frac{V_p - V_o}{V_o \; V_p}\right]$$

or

$$L = \left[\frac{V_o \; V_p}{V_p - V_o}\right] \left[(T_u - T_l)\right]$$

This approximation assumes that the depth of the plug is negligible. If the top of the plug is moved downward, then the width of the plug must be increased.

Using this equation, the observed velocities, and the observed travel-time lead, we obtain a width for the plug of 5.4 km, which agrees closely with the surface geological indications of the size of the caldera and the gravity solution (Strange, Woollard, and Rose, p. 381 in this issue).

Some control on the horizontal position of the plug exists in the present data. The previously mentioned reflections occurring at about 2 sec after the shot time in the distance range 3.8–6 km correspond to reflections from a depth of about 3 km outside the boundary of the plug, as shown on Figure 7. This, incidentally, is of the same order as the depth extrapolated for the magma chamber under Kilauea by Eaton (1962). Therefore, we tentatively identify these as being from an existing or former magma chamber.

Assuming a geometrical ray path, one can obtain an inner bound from the onset of the effect of the plug. The plug effect would then persist along the line for about 5 or 6 km. There is some additional constraint on the outer limit from the critical angle at which the refraction from the plug occurs. The critical angle to the plug is about 41° for the velocities used here, so the refractions from the high velocity layer extend beyond the outer edge of the dome to a distance roughly equal to the dome's depth. This corresponds in the present case to a point about 11.7 km from the shot point. For a model depth of 2 km, the top of the plug begins to curve downward at about 10 km from the shot point along the recording line.

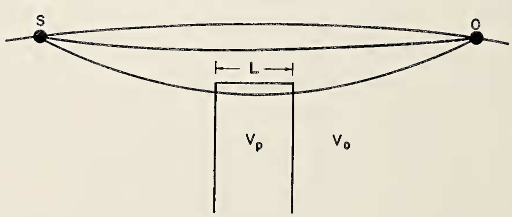

FIG. 8. Relation of transit times for paths inside and outside the plug.

The velocities observed here should be compared with those obtained by Manghnani and Woollard (p. 291 in this issue) on ultrasonic measurements of Hawaiian rocks, and with seismic velocities obtained by Raitt (1956), Shor and Pollard (1964), and the Western Geophysical Company (unpublished).

Current refraction work by the U. S. Geological Survey on the island of Hawaii substantiates the results of Eaton (1962) with respect to velocity and depth (D. Hill, personal communication). The Koolau caldera is somewhat unusual compared with those on the island of Hawaii because the gravity and magnetic anomalies are concentric to the geologic expression of the caldera. On the island of Hawaii the gradients are lower, indicating a greater depth to the plug, and the anomalies are usually shifted southward, usually in a greater amount for the older calderas. Only at Kilauea do the anomalies appear to be nearly concentric with the surface caldera.

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